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Method of manufacturing an electronic device and electronic device

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Method of manufacturing an electronic device and electronic device

The invention relates to a method of manufacturing an electronic device being provided with a microelectromechanical system (MEMS) element that comprises:
- a piezoelectric element with a piezoelectric layer sandwiched between a first and a second electrode, that is substantially freestanding, is mechanically supported through a support present on a substrate, and is electrically coupled to conductors on the substrate;
- a first and a second MEMS electrode, which first electrode is present at a surface of the piezoelectric element, and which second MEMS electrode is present at a surface of the substrate, which first and second MEMS electrode are mutually separated by an air gap, and which first MEMS electrode is movable towards and away from the second MEMS electrode by application of a driving voltage to the piezoelectric element.

The invention also relates to an electronic device provided with such a MEMS element.

Such a method and such a device are known per se in the art. In the known method, use is made of a sacrificial layer. After provision of the second MEMS electrode on the surface of the substrate, a sacrificial layer is provided and patterned in the desired pattern. The mechanical support, that also is or includes the electrical coupling is then provided. A conductive layer for the first MEMS electrode and the first electrode of the piezoelectric element, the piezoelectric layer and a further conductive layer are then applied. Finally, the sacrificial layer is removed, and the piezoelectric element is made freestanding.

It is a disadvantage of the known method that it severely limits the choice of materials and process options. The sacrificial layer must withstand the processing temperature of the piezoelectric layer. However, particularly for ceramic piezoelectric layers that are provided in a wet-chemical process, higher temperatures up to 800 degrees Celsius are necessary, in view of the required sintering. Examples of such layers include materials from the family of perowskite materials, including for instance lead lanthane zirconate titanate (PLZT), lead zirconate titanate (PZT) and lead magnesium niobate lead titanate (PMN PT). It is very hard, if not impossible to find sacrificial layers that withstand such

temperatures and nevertheless can be adequately removed afterwards, with a dry or wet-chemical treatment. Alternatively, another piezoelectric layer or another processing of piezoelectric layers must be found. The perowskite piezoelectric layer has the advantage over other layers, such as tantalum oxide, that its piezoelectric effect is much larger. The wet-chemical processing, and particularly the sol-gel process, has however the advantage above other processes, that it is cheap and that uniform layers with a good density can be obtained.

It is therefore a first object of the invention to provide a method of the kind mentioned in the opening paragraph, with which a wide range of materials and process options can be used, and with which particularly the piezoelectric layer can be a perowskite type layer that is applied with wet-chemical processing.

This object is achieved in that the method comprises the steps of:

– providing the substrate with at the surface the second MEMS electrode and a plurality of second bonding pads, said bonding pads being provided at their surface with a bondable material;
– providing a carrier with thereon the second electrode, the piezoelectric layer and the first electrode of the piezoelectric element, the first MEMS electrode and a plurality of first bonding pads, said bonding pads being provided at their surface with a bondable material;
– applying the carrier on top of the substrate such that the first bonding pads will be in contact with the second bonding pads one by one;
– bonding the first and the second bonding pads to form an electrical connection and the mechanical support; and
– removing the carrier at least partially, therewith allowing the piezoelectric element to be substantially freestanding.

According to the invention, use is made of a carrier in addition to the substrate. It is on the carrier that the piezoelectric layer is processed and only afterwards, the carrier and the substrate are assembled using bonding as a technique to provide the necessary electrical and mechanical connections. Finally, the carrier is at least partially removed. The proposed processing has the advantage, that no sacrificial layer is needed.

Another process for the manufacture of such a device is known, in which part of the substrate is removed at the area overlapping with the piezoelectric element. It is however a disadvantage of such a process, that one needs photolithography at the two opposed sides of the substrate. Furthermore, the substrate stability is substantially

diminished, due to the hole under the piezoelectric element. Another problem of the resulting device is the need for additional protecting members at both of the opposed sides of the substrate, in order to encapsulate the MEMS element adequately.

In a preferred embodiment of the method of the invention, the piezoelectric layer is a perowskit material. Examples hereof are materials from the family of lead-titanate-zirconate (PZT), including $PbZrTiO_3$, $Pb(X_{.33}Nb_{.67})O_3$-$PbTiO_3$, with X = Mg, Zn, Ni, or other, $Pb(Y_{.5}Nb_5)O_3$-$PbTiO_3$, with Y = Sc, Mn, In, Y, or other, which materials may be doped with a metal such as La, Mn, W, Fe, Sb, Sr and Ni. These materials are preferred in view of their good processability through sol-gel precursors with relatively moderate sintering temperatures of 800 °C or less, and their controllable microstructure, also if processed at large substrates of a diameter of 6" or even more. Other perowskite materials that can be used include for instance $Sr_3TaGa_3Si_2O_{14}$; $K(Sr_{1-x}Ba_x)_2Nb_5O_{15}$, where $(0 \le x \le 1)$; $Na(Sr_{1-x}Ba_x)_2Nb_5O_{15}$, where $(0 \le x \le 1)$; $BaTiO_3$; $(K_{1-x}Na_x)NbO_3$, where $(0 \le x \le 1)$; $(Bi,Na,K,Pb,Ba)TiO_3$; $(Bi,Na)TiO_3$; $Bi_7Ti_4NbO_{21}$; $(K_{1-x}Na_x)NbO_3$–$(Bi,Na,K,Pb,Ba)TiO_3$, where $(0 \le x \le 1)$; $a(Bi_xNa_{1-x})TiO_{3-b}(KNbO_{3-c})^1/_2(Bi_2O_3–Sc_2O_3)$, where $(0 \le x \le 1)$ and $(a + b + c = 1)$; $(Ba_aSr_bCa_c)Ti_xZr_{1-x}O_3$, where $(0 \le x \le 1)$ and $(a + b + c = 1)$; $(Ba_aSr_bLa_c)Bi_4Ti_4O_{15}$, where $(a + b + c = 1)$; $Bi_4Ti_3O_{12}$; $LiNbO_3$; $La_3Ga_{5.5}Nb_{0.5}O_{14}$; $La_3Ga_5SiO_{14}$; $La_3Ga_{5.5}Ta_{0.5}O_{14}$; AlN; ZnO.

The carrier in the method of the invention can principally be of any desired material, as long as it withstands any heat generated during sintering of the piezoelectric layer. Good examples include metal substrates in the first place and secondly ceramic substrates and the like. An example of a metal substrate is a bilayer substrate of aluminum and copper, wherein the copper is used as a conductive layer and the aluminum is removed. Other varieties hereof are for instance a three layer substrate of copper, aluminum and copper; of copper, a barrier layer such as NiAu and copper and the like. Examples of ceramic substrate include one or more layers of alumina, silica, glass, silicon or any other semiconductor material. Silicon and glass are advantageous embodiments, as silicon substrates can be processed using the infrastructure of standard semiconductor equipment and factories, and glass has the advantage of transparency.

The removal of the carrier can be achieved with etching, grinding, polishing and other techniques known to the skilled person, as well as with combinations thereof. For piezoelectric layers with a low sintering temperature, use could be made of a connection with an adhesive, wherein the adhesive is removed or the adhesive force diminished through exposure to UV-radiation or through heating. Generally, it is not necessary that the carrier is

removed completely. Parts may be left and can be used as a part of a package or for contacting the device to an external element, or for the provision of specific components, or for the provision of a heat sink, heat pipe or the like.

It is preferable to use a structural layer in combination with the piezoelectric element, so as to provide an assymmetry needed for bending in the desired direction. The structural layer will be present at the side of the piezoelectric element facing away from the substrate. More preferably, in combination with a carrier that is at least partially to be removed with etching, and particularly with silicon, glass or the like as a carrier, such structural layer will act also as etch stop layer and optionally as a barrier layer. Good examples include silicon oxide, silicon nitride, magnesium oxide, zirconium oxide, aluminum oxide, titanium oxide. A bilayer including two of these materials may be used.

The following general insight has however been found by the inventors, that the structural layer is not necessary for the operation of the device. It is sufficient that the first and second electrode are of different material and/or of different thickness, so as to provide assymmetry and allow bending in the direction from and towards the second MEMS electrode. Particularly, it is preferred that the second electrode of the piezoelectric element which faces away from the substrate, is thicker than the first electrode. Ideally, for the case that both electrodes comprise the same metal, and particularly Pt, the thickness of the second electrode is equal to the sum of twice the thickness of the first electrode and half the thickness of the piezoelectric layer. Practically, if the materials of both electrodes are the same, then the thickness ratio is between 4 and 10; if dissimilar materials are used their thicknesses should be adjusted so that the ratio of their bending resistances is equal to that of the two electrodes of of the same material with a thickness ratio between 4 and 10.

The second electrode is preferably part of an electrode layer. In case of use of a perowskit material such as a PZT-type of material, it is preferred to use noble metals. However conductive oxides such as Ruthenium oxide and the like can be used alternatively. It is even possible to use base metal electrodes, for instance nickel or copper, in combination with some processing conditions and aftertreatments in a reducing atmosphere. Due to the provision of the piezoelectric layer on a separate carrier, such an aftertreatment is by no means impossible as it would be in the case of processing on a single substrate with sacrificial layers.

The first electrode is preferably part of an electrode layer, in which also the first bonding pads, and a vertical interconnect through the piezoelectric layer are defined. As this first electrode is provided on top of the piezoelectric layer, and after the sintering thereof,

this layer can be made of any conductive material. Such conductive material has at least two advantages, above the use of a noble metal or a conductive oxide, and platinum in particular. First of all, the conductivity may be higher. Hence, the resistance of the vertical interconnect is thus reduced. Secondly, the adhesion of platinum to a perowskit layer is a well-known problem in the art. Such weak adhesion at the area where the beam is connected to the support would be a threat to the lifetime of the MEMS element of the invention. In the invention, this problem is prevented, as the platinum is not present there.

The mechanical support is in the invention a bump-like construction. Several bump types (stud bumps, solder balls, electroplated columns) of several materials (copper, solder, electroless nickel or tin) are known in the art of assembly. They are can be chosen to fulfill boundary conditions of height, diameter, pitch, temperature stability etc. For the present application, it is desired that the height can be defined well, as the distance beween the first and second MEMS electrode influences switch and capacitive properties of the MEMS element. Good examples include layers that are relatively stable in temperature, such as columns of Cu, Ni or the like, or metal bases of for instance TiW and Au with a solder layer of for instance Sn. If desired, use can be made of a sacrificial layer. Such a sacrificial layer can be applied after processing of the piezoelectric layer, and can be removed by etching once the mechanical support is formed. Alternatively or additionally, use could be made of additional supports of one or more stable material, that need not to be bonded so as to form an electrical connection. Such a stable material of an additional support is for instance SiO_2.

Another option would be the use of protrusions on the substrate. Then, the conductive layer of the first electrode is elevated as a consequence of processing, and need not to be thickened anymore. The protrusion has at the same time the advantage of patterning the piezoelectric layer. Moreover, etching through this protrusion to form a vertical interconnect may well be simpler than etching through a piezoelectric layer of a complex oxide material, and particularly of a material including lead. In a very specific modification, it is not even necessary to form vertical interconnects. In this embodiment, the one electrode layer is contacted at one protrusion and the other electrode layer is contacted at another protrusion.

The MEMS element can be construed in different ways. The piezoelectric element, that effectively is a beam, may be embodied both as a single clamped beam and as a double clamped beam. In the case of a single clamped beam it appears beneficial to prestress the beam. This means that it is provided with a determined curvature at zero actuation

voltage. By application of an actuation voltage the piezoelectric layer will show expansion in a direction substantially perpendicular to the orientation of the applied electric field. Hence, it will become less curved, and the capacitance between the first and second MEMS electrodes will increase, or electrical contact between the first and second electrodes will be established. Experiments have shown that this flattening can indeed be achieved.

This prestressed beam can be used generally. It can be combined advantageously with the present invention, and in particular the embodiment in which the carrier is removed only partially. The carrier may then act as a spacer, such as to protect the beam that extends in the situation of zero actuation voltage in the space created by the local carrier removal. The advantage of this embodiment is particularly, that the height of the metallic contacts between substrate and carrier can be kept small; the metal needed for the connection can thus be applied easily with standard thin-film processing.

It is a second object of the invention to provide a device with a MEMS device as mentioned in the opening paragraph, that has a better mechanical stability.

This second object is achieved in that the mechanical support comprises first and second bonding pads present at the surfaces of the piezoelectric element and the substrate that face each other, as well as bonding material there between of a desired height, which support also functions as electrical interconnect. The construction of a MEMS element that is built up from two parts that are assembled together with bumps is found to lead to a better mechanical stability, particularly for the case that the piezoelectric layer is a perowskit layer. This is due to the fact that each of the parts can be manufactured separately, and thus under optimal conditions. Furthermore the mechanical support can be built up of layers that need to withstand only limited temperature, as compared to the sintering temperature of the piezoelectric layer. Another factor contributing to the mechanical stability is that the manufacture of the device, including a further capping layer for packaging if so desired, can be done at wafer level, and as such the tolerance per device can be effectively reduced.

In a preferred embodiment, the piezoelectric element is provided with a vertical interconnect through the piezoelectric layer, interconnecting the support and the second electrode of the piezoelectric element, which vertical interconnect comprises the same material as the first bonding pad and the first electrode of the piezoelectric element. This embodiment is suitable in that herein the material of the vertical interconnect is a material that need not to withstand the sintering temperatures of the piezoelectric layer, as in the prior art. It thus can be chosen so as to have optimal electrical conductivity. The use of the same

material for the interconnect, the bonding pad and the first electrode allows to simplify the processing of this element, and also contributes to the adhesion: the vertical interconnect structure will lead to some mechanical anchoring of the metal into the piezoelectric layer. It is however observed for the sake of completeness, that the vertical interconnect could also be present within an insulating island or that the piezoelectric layer is patterned and the second electrode is exposed to the surface at which it is designed to be a bonding pad.

In another embodiment, a patterned carrier layer is present, said patterned carrier layer being connected to the piezoelectric element at the side thereof facing away from the substrate. As stated with reference to the method, it is with the help of a carrier layer that the device of the invention can be made advantageously. Examples of carrier layers are mentioned with reference to the method. However, it appears attractive that the carrier layer is not completely removed, but only partially. In this manner, it can be used for the provision of additional functionality, and as part of a package of the MEMS element – i.e. forming the sidewalls of a cavity.

One suitable embodiment of the additional functionality is that the patterned carrier layer is provided with contact pads for coupling to an external device. Herein, the patterned carrier is used as the chip carrier for the substrate. It may be then, that more than one chips are attached to the patterned carrier. The needed package for the MEMS element is then formed by the patterned carrier layer and the surface of the said external device.

Another suitable embodiment is that the piezoelectric layer is furthermore used at an area lateral to the MEMS element as dielectric of a capacitor.

A further suitable embodiment, in the case that the carrier layer comprises a semiconductor material, is that transistors and/or other driving electronics are provided, that are needed for driving the MEMS element. This is not only an effective use of space, but also allows that the driving electronics can be located near to the MEMS element, while the distance between the MEMS element and other structures need not to be large.

A further alternative embodiment is that one or more of the metal layers used for the electrodes of the piezoelectric elements are also used for the definition of inductors. Generally, inductors are, like MEMS elements, relatively large structures in comparison to transistors. By definition of all these large elements at or one the patterned carrier layer, it is possible that the substrates assembled therewith are advanced integrated circuits with high costs per device, and/or possibly substrates of a material that does not fit with the definition of high-quality inductors and coils.

Another suitable embodiment is that the patterned carrier layer at its side facing away from the substrate provided with a closing member, that closes a cavity in which the MEMS element is present, side walls of the cavity being formed by mechanical support structures. This embodiment provides the said package. The closing member may be provided with contact pads, heat sinks and other desired structures. Examples of closing members include glass plates, ceramic layers and metal layers. Such glass plate may contain electrically conductive wires or structures oriented substantially normal to the plane of the glass plate.

Basically and generally, the MEMS element can be embodied in at least four different versions: switch, capacitor, sensor, resonator. In one embodiment the MEMS element is a switch, the first MEMS electrode and the first electrode of the piezoelectric element being integrated into one. The advantage of piezoelectric switches over electrostatic switches are that the piezoelectric switches can operate with lower actuation voltages and that the stitching force is diminished. By provision of the either the one or the other electrode of the piezoelectric element in sufficient thickness, the high-frequent signal can be provided with low loss. This thick layer may also be the layer of the second electrode facing away from the substrate, as the high dielectric constant of the piezoelectric layer allows sufficient capacitive coupling with the first MEMS electrode.

In another embodiment the MEMS element is embodied as a capacitor, the first MEMS electrode and the second electrode of the piezoelectric element being integrated into one. This embodiment has the advantage that the variety in capacitance values can be very large. Moreover, the resulting capacitor has a large breakdown voltage, in the order of 20 to 150 V. This is the result of the piezoelectric layer acting as the dielectric layer and being part of the beam-shaped piezoelectric element. The high dielectric constant of many piezoelectric materials, particularly again the perowskite type materials of f.i. the leadtitanate and the bariumtitanate families, allows a large capacitance per unit of surface area for layer thicknesses that are larger than about 25-50 nm. This large thickness provides a high breakdown voltage and a low leakage current.

These and other aspects of the method and the device of the invention will be further elucidated with reference to the figures, in which:

Figs. 1-3 show diagrammatically and in cross-section the results of different steps in the method;

Fig. 4 shows diagrammatically a cross-sectional view of the device according to a first embodiment, resulting from the method steps as shown in Fig. 1 to 3;

Fig. 5 shows diagrammatically a cross-sectional view of the device according to a second embodiment;

Fig. 6 shows diagrammatically a cross-sectional view of the device according to a third embodiment;

Fig. 7 shows diagrammatically a cross-sectional view of the device according to a fourth embodiment;

Fig. 8 shows diagrammatically a cross-sectional view of the device according to a fifth embodiment;

Fig. 9 shows diagrammatically a cross-sectional view of a MEMS device;

Fig. 10 shows a sketch of a MEMS device, for explanation of a specific embodiment; and

Fig. 11 shows a graph of results corresponding to the MEMS device as sketched in Fig. 10.

The figures are not drawn to scale and equal parts in different figures will be referred to with the same reference numbers.

Fig. 4 shows an electronic device with the MEMS element 100. Fig. 1-3 show different stages in the method of the invention, resulting in the formation of this device with the MEMS element 100 as shown in Fig. 4. This device 100 comprises a piezoelectric element 40 and a substrate 30. The piezoelectric element 40 is provided with a piezoelectric layer 25, a first electrode 21 and a second electrode 22. It is supported mechanically through a support 38, that is present on the substrate 30. The device 100 further comprises a first MEMS electrode 41 and a second MEMS electrode 31. In this example, the first MEMS electrode 41 is integrated in the first electrode 21 of the piezoelectric element 40, but that is not necessary. On application of a driving voltage on the piezoelectric element 40, e.g. between the first and the second electrode 21,22 thereof, the first MEMS electrode 41 is movable towards and/or away from the second MEMS electrode 31. There are different options of moving the beam-shaped piezoelectric element, and therewith the first MEMS electrode 41. Generally, the first MEMS electrode 41 will be moved towards the second MEMS electrode 31 on application of a driving voltage, and will relax to its position away from the second MEMS electrode 31 after removal of the driving voltage. If the MEMS

element is a switch, having a closed state in which the first and the second MEMS electrode 41,31 are in contact with each other, then a threshold voltage is needed in general to overcome stitching forces that keep the first MEMS electrode 41 attached to the second MEMS electrode 31.

The MEMS element 100 as shown in Fig. 4 has the piezoelectric layer 25 as the carrying layer of the beam-shaped piezoelectric element. In this case, the piezoelectric layer 25 comprises lead lanthane zirconate titanate in the composition of $Pb_{1.02}La_{0.05}Zr_{0.53}Ti_{0.47}O_3$ and includes a first layer of lead zirconate titanate as a nucleation layer. A vertical interconnect 23 is present in the piezoelectric layer 25 so as to connect the second electrode 22. This interconnect 23 is made by wet-chemical etching, for instance with the method as described in US4,759,823. The second electrode 22 comprises Ti/Pt and the first electrode 21 comprises two sublayers of TiW and Al. The piezoelectric element 40 further comprises a structural layer 13, in this case of silicon nitride and a barrier layer 24, in this case of TiO_2. Bondpads 26 are defined in the layer of the first electrode 21, which bond pads 26 are covered by solderable metal, in this case layers 15, 16, 36, 35 of TiW/Au and Sn, each with a thickness in the order of 1 to 5 μm. Due to the connection of TiW/Al, TiW/Au, the bond pad structure has a good mechanical stability. Due to the use of TiW/Al the conductivity of the vertical interconnect 23 is excellent. The substrate 30 is in this case a silicon substrate covered with a thermal oxide layer 32 and comprises active elements needed for driving the MEMS element 100 as well as any other active element, passive elements that may be integrated into filters and integrated circuits, as desired. As the skilled person will understand, the driving electronics for the MEMS element 100 could also be provided in the carrier layer if only partially removed. This is a matter of design and depends on the amount of functionality needed as well as the quality of the substrate material needed for the provision of driving electronics.

Fig. 1 shows a cross-sectional view of the first stage of the method, in which a carrier 10 having a first and a second surface 11,12 is provided. In this example, the carrier 10 is a substrate of silicon. It is provided with a number of layers that are deposited by any wet-chemical or vapour deposition methods, as known per se to the skilled person. The advantage of this carrier is that it can be processed in an non-advanced semiconductor fab with lithographic equipment providing a resolution of a micron or the like. The processing can be optimized so as to achieve a good adhesion between the piezoelectric layer 25 and the electrodes 21,22, and to achieve optimum performance of the piezoelectric layer 25. It will be understood that the carrier 10 may be manufactured in the same fab as the assembly, but also

separately. The carrier 10 is furthermore provided with a plurality of first bond pads 26. Although only one bond pad is shown, it will be understood by the skilled person that generally more bond pads 26 are present so as to achieve the required mechanical stability, or that the first and second bond pads have an elongated shape so as to achieve the same result. The first bond pads 26 carry layers 15,16 of solderable material of a desired height.

Fig. 2 shows a cross-sectional view of a second stage of the method. At this stage, a substrate 30 is provided. This substrate 30 is provided with the second MEMS electrode 31 and with second bond pads 36, that are provided with a further solderable layer 35. The carrier 10 is then applied on top of the substrate 30, such that the first bond pads 26 are in electrical contact with the second bond pads 36 through the solderable layers 15,16,35. It will be understood that the substrate 30 may alternatively be provided on the carrier 10, or that the carrier 10 and the substrate 30 may be put together in a desired manner, particularly if the assembly occurs on wafer-level scale. Alignment means may be present for the alignment of the carrier 10 and the substrate 30. These may for instance be mechanical alignment means, using a lock-key mechanism. Alternatively, the carrier 10 may be transparent allowing alignment with optical means.

Fig. 3 shows the assembly 100 after bonding and thus forming the electrical connection and the mechanical support. The bonding process of this example is a thermal-compressive bonding process, but this is not essential.

Fig. 4 shows the final device after removal of the carrier 10. In this example, the carrier 10 is removed completely, starting from the second side 12 and extending up to the structural layer that acts as an etch stop layer 13. Then, the structural layer 13 is patterned with the help of a laser, or alternatively with other lithography. It is herewith observed that the structural layer can also be patterned before deposition of the piezoelectric layer 25, or be removed in the same patterning operation as the patterning of the piezoelectric layer. The carrier 10 could be pre-etched in this same etching operation, using dry or wet-etching. Although preferred to remove the carrier 10 completely, it is also possible that a thin layer thereof is preserved locally. Thin layers of silicon show sufficient flexibility. Moreover by setting the thickness of the silicon which is possible through an adequate control of etching, the flexibility can be tuned. Therewith, also the maintained layer of silicon can be used as the structural layer. If desired for the mechanical stability during the removal of the substrate, particularly if use is made of grinding and polishing techniques, then the air gap between the piezoelectric element 40 and the substrate 30 can be filled with a sacrificial layer, to be

removed afterwards. Such a sacrificial layer could well be a fluid layer, and have a viscosity that strongly reduces on gentle heating.

Fig. 5 shows diagrammatically a cross-sectional view of a second embodiment of the device of the invention. The MEMS element 100 of this embodiment comprises a carrier 10 that is removed only locally, and subsequently provided at its second side with a closing member 60. The closing member 60 is in this case a layer of glass, but can be of any material or even more than one material. The connection between the closing member 60 and the carrier 10 can be realized with solder, glue or else. A solder or metal connection is preferable so as to allow a vacuum encapsulation of the MEMS element. The closing member 60 can be provided with electrically conducting interconnects extending from the interface with the carrier 10 to the opposed surface. This allows the use of this side of the device as the contact layer for contacting to external devices. Moreover, in case that the closing member comprises glass, it could be used as a substrate for an inductor or for a dipole structure for use as an antenna. If the closing member 60 comprises glass, any desired shapes to improve accomodation of such conductive structures and adhesion to the carrier can be provided suitably with powder blasting techniques. In another advantageous embodiment, the closing member 60 may be a metal layer, and the closing member may extend laterally beyond the MEMS element to act as a leadframe. In that case the substrate 30 with other functionality may extend laterally, and have bond pads, that are with solder or metal bumps connected to said leadframe. An advantageous type of leadframe is for instance known as the HVQFN-leadframe. Although shown here to be planar, it is not excluded that the beam-shaped piezoelectric element 40 is in effect pre-stressed and bent without the application of a driving voltage.

Fig. 6 shows diagrammatically a cross-sectional view of a third embodiment of the device of the invention. In this embodiment, it is not the substrate 30, but the carrier 10 which forms the carrying layer for the device that includes more than only the MEMS element 100. The carrier 10 also carries a further device 80, in this case an integrated circuit. It is provided with bumps 88 to the carrier 10 in known manner. The piezoelectric layer 25 can be provided only locally, in that use is made of a resist material having a stability at the sintering temperature of the piezoelectric layer. This is for instance silicon oxide or the like. The carrier 10 is in this example provided with U-shaped end contacts 91, 92, extending from the first side 11 to the second side 12 of the carrier 10 and allowing surface mounting of the device 100 on an external carrier, or on a leadframe. In order to form a completely insulated cavity, the support 38 is preferably ring shaped. Alternatively, an additional ring shaped

closure can be provided, acting both as support and as isolation, and if desired as electrical connection.

Fig. 7 shows diagrammatically a cross-sectional view of a fourth embodiment of the device of the invention. In this embodiment, use is made of a double-clamped beam 40. A specific feature of this double clamped beam 40 is that it comprises protrusions 18. The protrusions comprise for instance of silicon oxide, but could be part of a glass or alumina substrate that has been provided in a desired shape in advance of applying the piezoelectric layer 25. These protrusions 18 allow a specific feature, in that the second electrode 22 of the piezoelectric element 40 can be contacted to the support 38 without the need of a vertical interconnect through the piezoelectric layer 25. Since the protrusions 18 may be given a shape as desired, this allows the provision of the piezoelectric layer without the need for etching. Moreover, although not shown here, the protrusions may have a height that is larger than that of the stack of first electrode 21, piezoelectric layer 25 and second electrode 22. This allows to use solder material of a very minimal height. It is furthermore observed that such protrusions can alternatively be used for improvement of the removal of the carrier 10. The effect of these protrusions 18 is that the structural layer 13, and/or a barrier layer 24 may extend along the side faces of these protrusions 18. At the same time, they can be removed on top of the protrusions 18 and elsewhere if not desired. Using the structural layer 13 as an etch stop layer, the piezoelectric layer 25 can be protected perfectly during the removal of the carrier 10. Nevertheless, there is no need for any lithographical step after removal of the carrier 10 and there is no need to use specific etchants or to control the etching specifically either. Suitably, the layer of the second electrode 22 is herein provided with a technique known per se as angle deposition, although other techniques are not excluded.

Fig. 8 shows diagrammatically a cross-sectional view of a fifth embodiment of the device of the invention. This embodiment is a capacitor. It has furthermore the feature that the first electrode of the piezoelectric element and the second MEMS electrode are positioned such, that on perpendicular projection the one does not have an overlap with the other.

The capacitor operates in the following manner: on application of an actuation voltage the piezoelectric element will bent towards the substrate. Then the piezoelectric layer will come into contact with the second MEMS electrode. The resulting capacitor essentially consists then of the second electrode 22 of the piezoelectric element 40 (in which the first MEMS electrode 41 is integrated), the piezoelectric layer 25 and the second MEMS electrode 31.

The advantage of this capacitor is the good isolation in the situation in which the MEMS element is opened, whereas the electric losses are nevertheless low. This is achieved in that the leakage current through the piezoelectric layer is very limited and that the piezoelectric element has a high breakdown voltage, for instance in the range of 20 to 150 V. This beneficial properties result from the density and the non-porous structure of the piezoelectric layer, and furthermore from the thickness of the piezoelectric layer, preferably of more than 200 nm.

Fig 9 shows an alternative realisation of the principle as shown in Fig. 8. The element 101 is specifically provided with an RF input 102 and an RF output 103. The structure shown is provided with a 0.5 μm thick piezoelectric layer 25, in this case essentially consisting of $PbZr_{0.53}Ti_{0.47}O_3$, and having a relative dielectric constant of about 1000. The second electrode 22 of the piezoelectric element 40 is herein a layer of TiW/Al or Al with a thickness of 1 μm. The first electrode 21 of the piezoelectric element 40 is a layer of Pt of 0.3 μm. The element is a capacitive switch of which the capacity in the closed state is limited by the surface roughness of the contacts 21, 31, which typically is in the order of 5 nm or more. This negatively affects the capacitance density. By using a dielectric with a high dielectric constant, the resulting capacitor is nevertheless dense enough, as the average dielectric constant is still rather large.

The same construction can be used as a galvanic switch as well. The idea behind this switch is that the second electrode 22 will be used for transfer of the high-frequency signal, therewith reducing the resistive losses. The high-frequency signal must pass the dielectric, but this is in practice not a disadvantage in view of the high dielectric constant, the high frequency and the fact that the capacitor area is as large as the complete piezoelectric element.

Fig. 10 shows a sketch of a functioning principle of a specific embodiment of the invention. Fig. 11 shows a graph with results corresponding to this embodiment. According hereto, the beam-shaped piezoelectric element 40 is pre-stressed. The piezoelectric element is clamped on one side and is provided on a mechanical support with a small thickness, in the order of 1-2 microns or less. A dielectric layer may be present if so desired. The device can be constructed to function in two different operation modes: in the first mode, the piezoelectric element is flat at zero actuation voltage. The actuation voltage is then used to increase the distance between the piezoelectric element 40 and the second MEMS electrode 31. The capacitance thus reduces with increasing actuation voltage. In the second, preferred mode, the piezoelectric element 40 has already a determined curvature at

zero actuation voltage. By application of an actuation voltage the piezoelectric element 40 can be moved towards the second MEMS electrode 31. The piezoelectric element 40 will become flat at a certain actuation voltage V_0. As can be seen in Fig. 11, the MEMS element can indeed be operated in the second mode in a reliable and effective manner.

CLAIMS:

1. A method of manufacturing an electronic device being provided with a microelectromechanical system (MEMS) element, that comprises:
- a piezoelectric element with a piezoelectric layer sandwiched between a first and a second electrode, that is substantially freestanding, is mechanically supported through a support present on a substrate, and is electrically coupled to conductors on the substrate;
- a first and a second MEMS electrode, which first electrode is present at a surface of the piezoelectric element, and which second MEMS electrode is present at a surface of the substrate, which first and second MEMS electrode are mutually separated by an air gap, and which first MEMS electrode is movable towards and/or away from the second MEMS electrode by application of a driving voltage to the piezoelectric element;
which method comprises the steps of:

- providing the substrate with at the surface the second MEMS electrode and at least one second bond pads, said bond pads being provided at their surface with a bondable material;
- providing a carrier with thereon the second electrode, the piezoelectric layer and the first electrode of the piezoelectric element, the first MEMS electrode and at least one first bond pads, said bond pads being provided at their surface with a bondable material;
- applying the carrier to the substrate such that the first bond pads will be in contact with the second bond pads one by one;
- bonding the first and the second bond pads to form an electrical connection and the mechanical support; and
- removing the carrier at least partially, therewith allowing the piezoelectric element to be substantially freestanding.

2. A method as claimed in Claim 1, wherein the piezoelectric layer is a perowskite material.

3. A method as claimed in Claim 1 or 2, wherein the second electrode of the piezoelectric element comprises a material chosen from the group of noble metals and conductive oxides.

4. A method as claimed in Claim 3, wherein the first electrode of the piezoelectric element, the first MEMS electrode, the first bonding pads and a first via from the first bonding pads to the second electrode of the piezoelectric element are provided in one layer of electrically conductive material.

5. A method as claimed in Claim 1 or 2, wherein

- the carrier comprises a ceramic substrate layer or a semiconductor substrate layer, and thereon an etch stop layer, and
- the removal of which ceramic or semiconductor substrate layer includes an etching treatment.

6. A method as claimed in Claim 5, wherein the substrate layer comprises silicon.

7. An electronic device being provided with a microelectromechanical system (MEMS) element, that comprises:

- a piezoelectric element with a piezoelectric layer sandwiched between a first and a second electrode, that is substantially freestanding, is mechanically supported through a support present on a substrate, and is electrically coupled to conductors on the substrate;
- a first and a second MEMS electrode, which first electrode is present at a surface of the piezoelectric element, and which second MEMS electrode is present at a surface of the substrate, which first and second MEMS electrode are mutually separated by an air gap, and which first MEMS electrode is movable towards and away from the second MEMS electrode by application of a driving voltage to the piezoelectric element;

characterized in that the mechanical support comprises first and second bonding pads present at the surfaces of the piezoelectric element and the substrate that face each other, as well as bonding material there between of a desired height, which support also functions as electrical interconnect.

8. An electronic device as claimed in Claim 7, characterized in that the piezoelectric element is provided with a vertical interconnect through the piezoelectric layer, interconnecting the support and the second electrode of the piezoelectric element, which vertical interconnect comprises the same material as the first bonding pad and the first electrode of the piezoelectric element.

9. An electronic device as claimed in Claim 7, characterized in that a patterned carrier layer is present, said patterned carrier layer being connected to the piezoelectric element at the side thereof facing away from the substrate.

10. An electronic device as claimed in Claim 9, wherein the patterned carrier layer is provided with contact pads for coupling to an external device.

11. An electronic device as claimed in Claim 9, wherein the patterned carrier layer at its side facing away from the substrate provided with a closing member, that closes a cavity in which the MEMS element is present, side walls of the cavity being formed by mechanical support structures.

12. An electronic device as claimed in Claim 7, wherein the substrate is provided with further elements.

13. An electronic device as claimed in Claim 7, wherein the MEMS element is embodied as a switch, the first MEMS electrode and the first electrode of the piezoelectric element being integrated into one.

14. An electronic device as claimed in Claim 7, wherein the MEMS element is embodied as a capacitor, the first MEMS electrode and the second electrode of the piezoelectric element being integrated into one, while the first electrode of the piezoelectric element is on perpendicular projection on the substrate surface free of overlap with the second MEMS electrode.

ABSTRACT

The method of manufacturing the MEMS element (100) comprises the step of assembly of a carrier (10) with a piezoelectric element (40) and with a first MEMS electrode (41) and of a substrate (30) with a second MEMS electrode (31). The device resulting after bonding and at least partial removal of the carrier (10) has a good stability and allows integration of several components and functionality.

Fig. 5

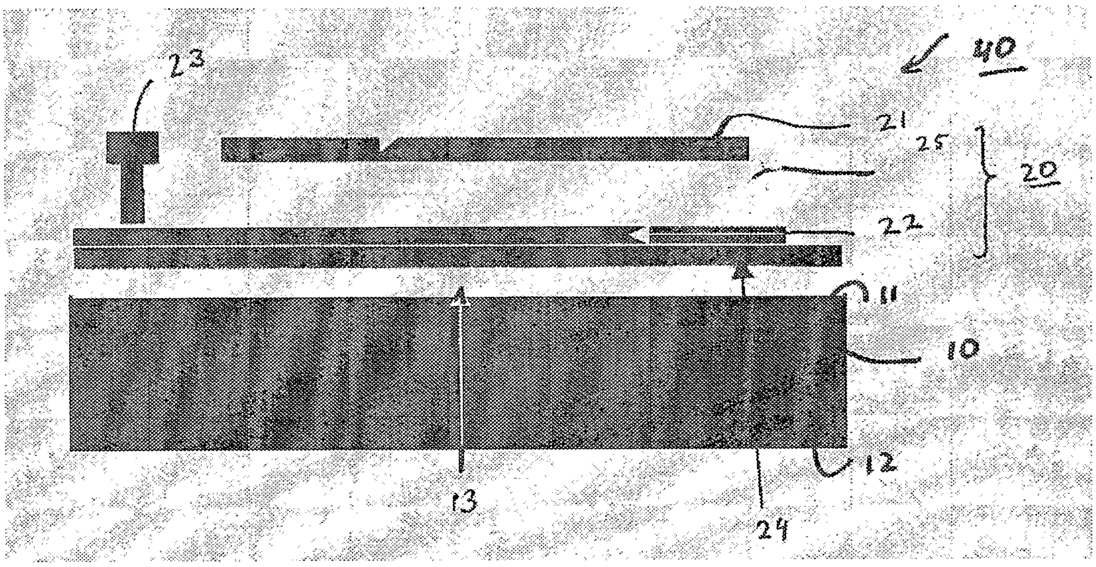


FIG.1

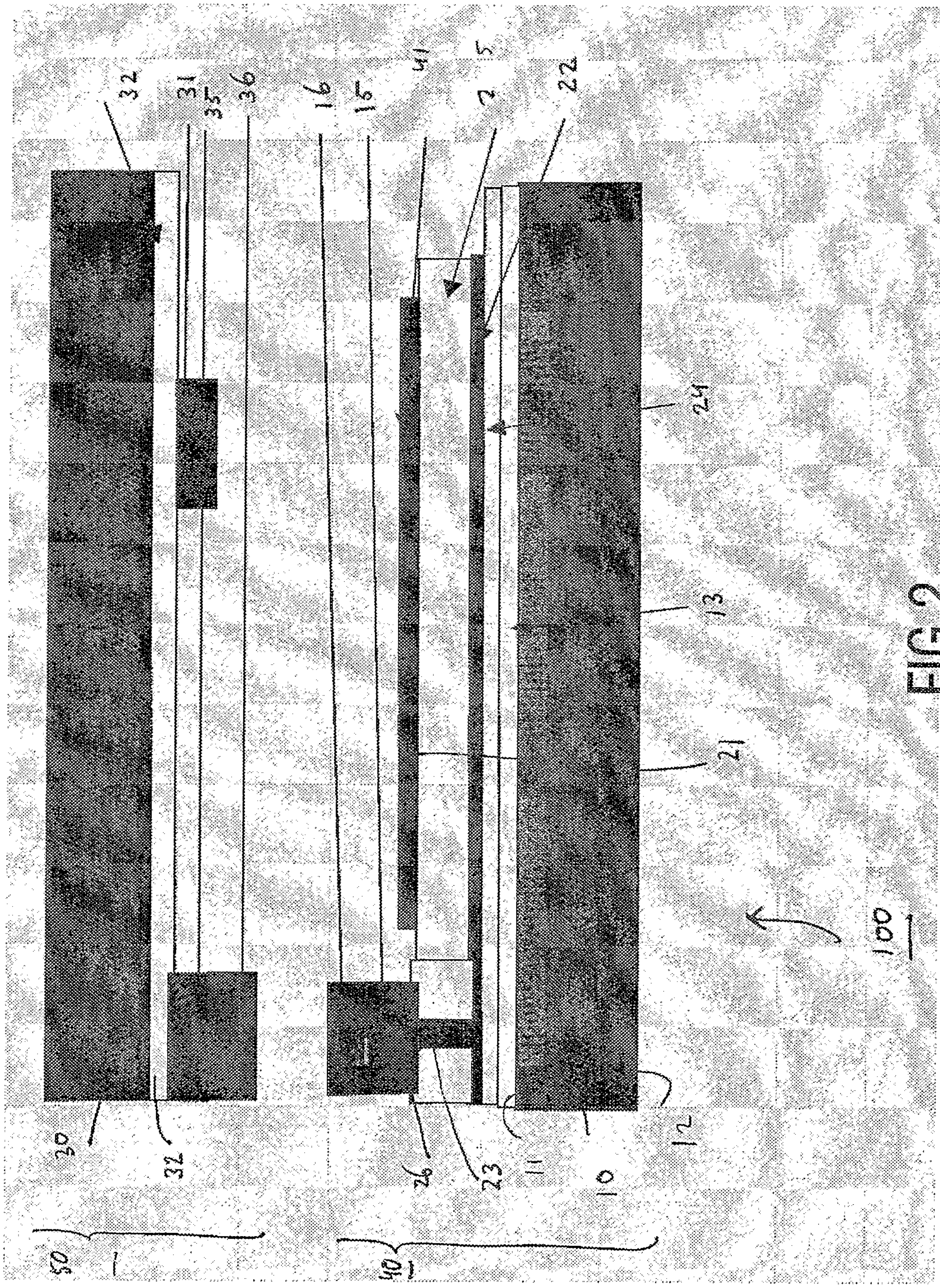


FIG.2

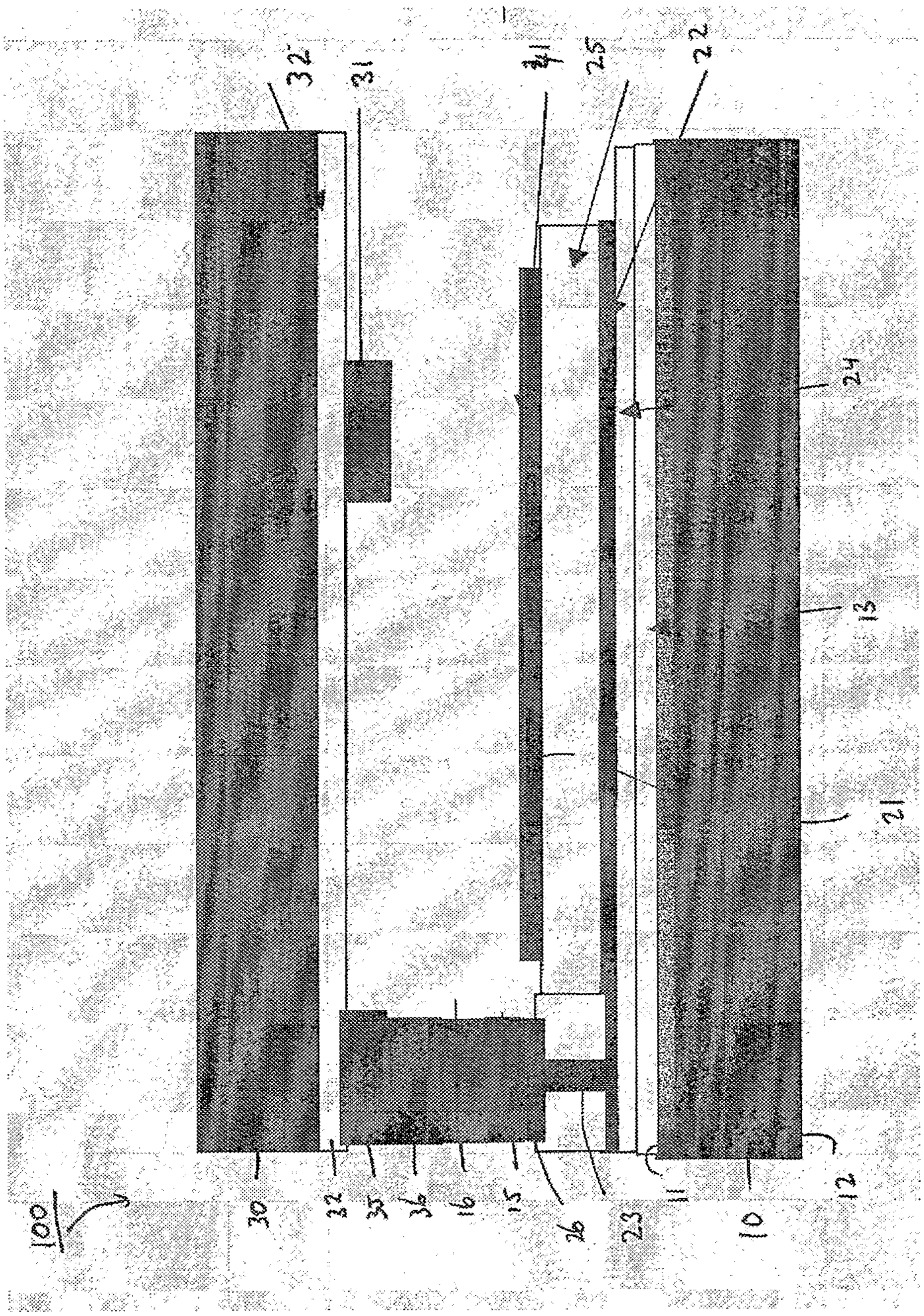


FIG.3

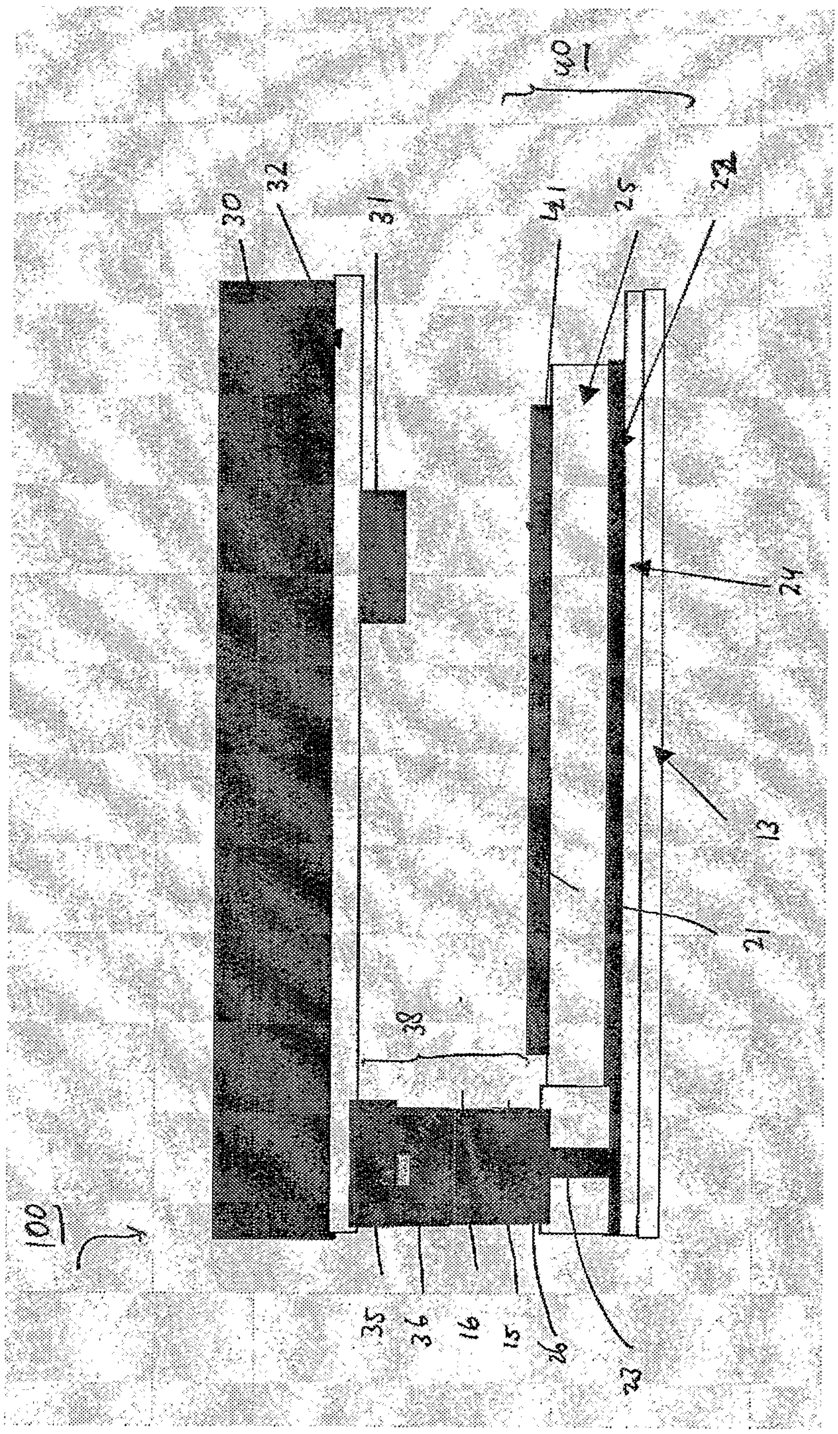


FIG.4

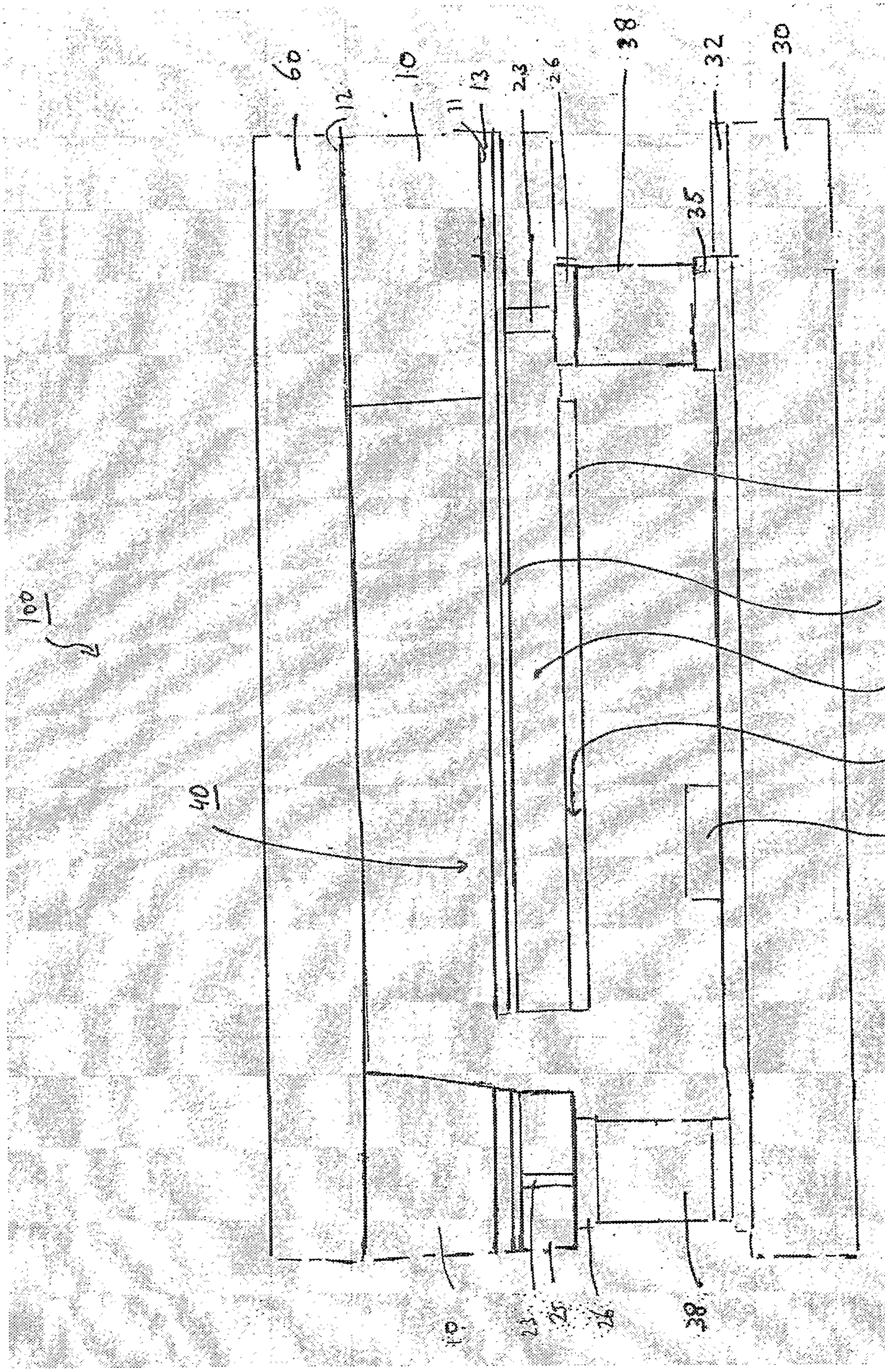
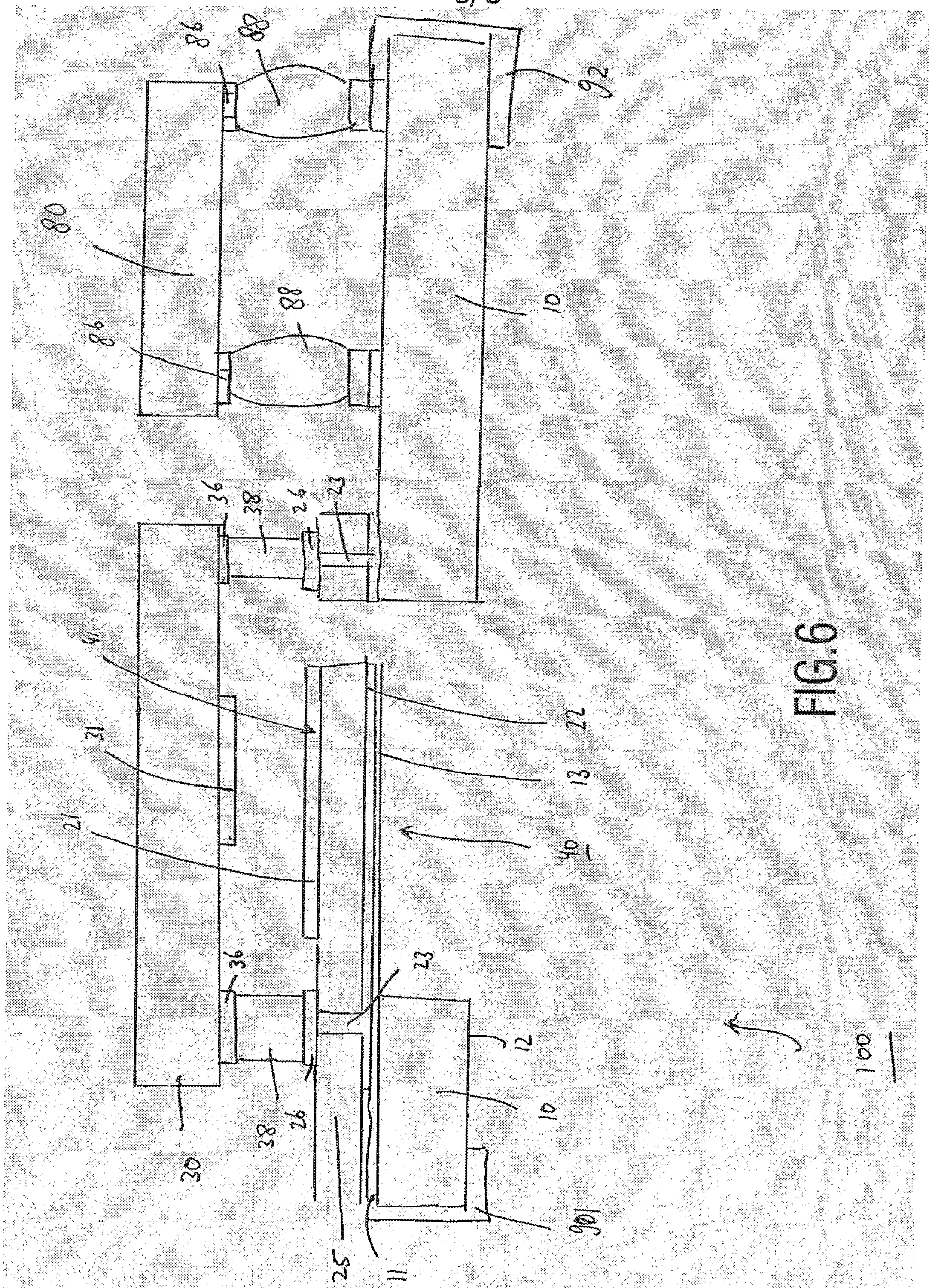


FIG.5


80
86
88
86
88
92
10
36
38
26
23
41
31
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22
13
40
36
23
12
30
38
26
10
100
25
11
90

FIG.6

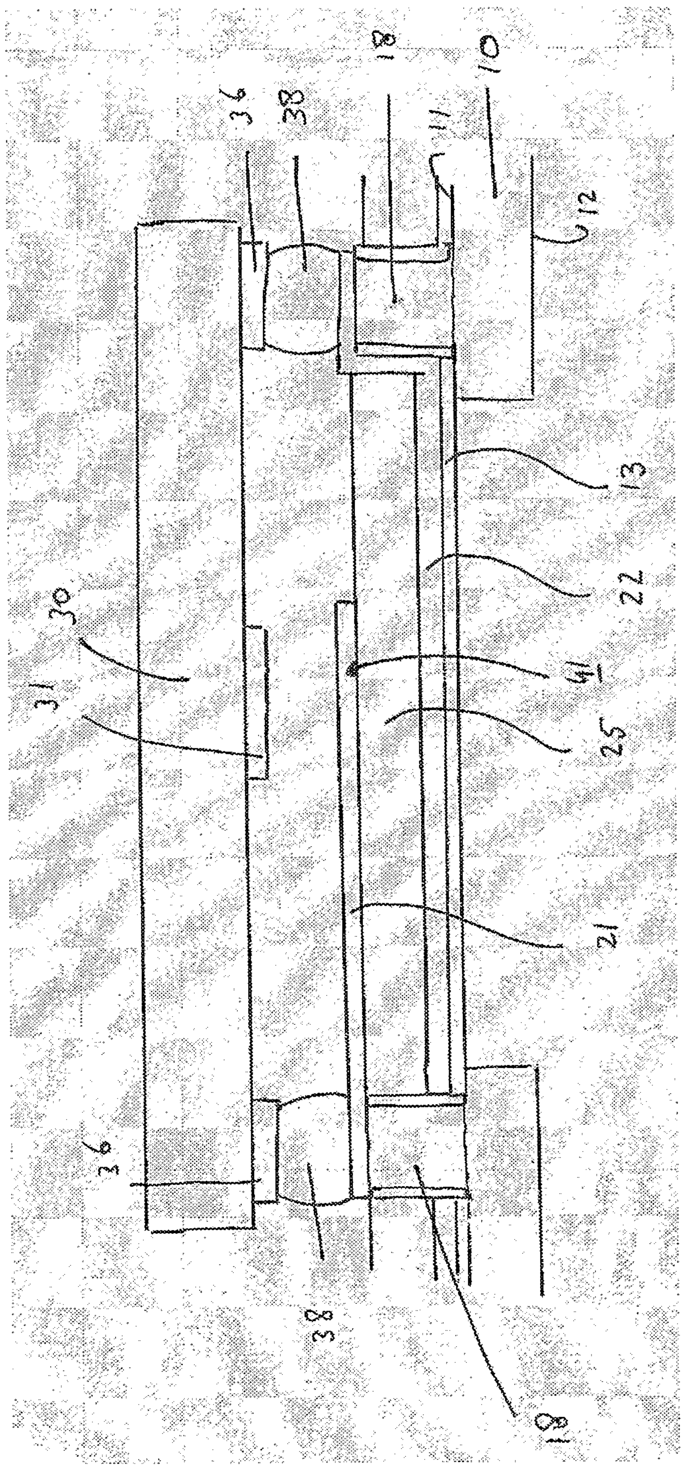
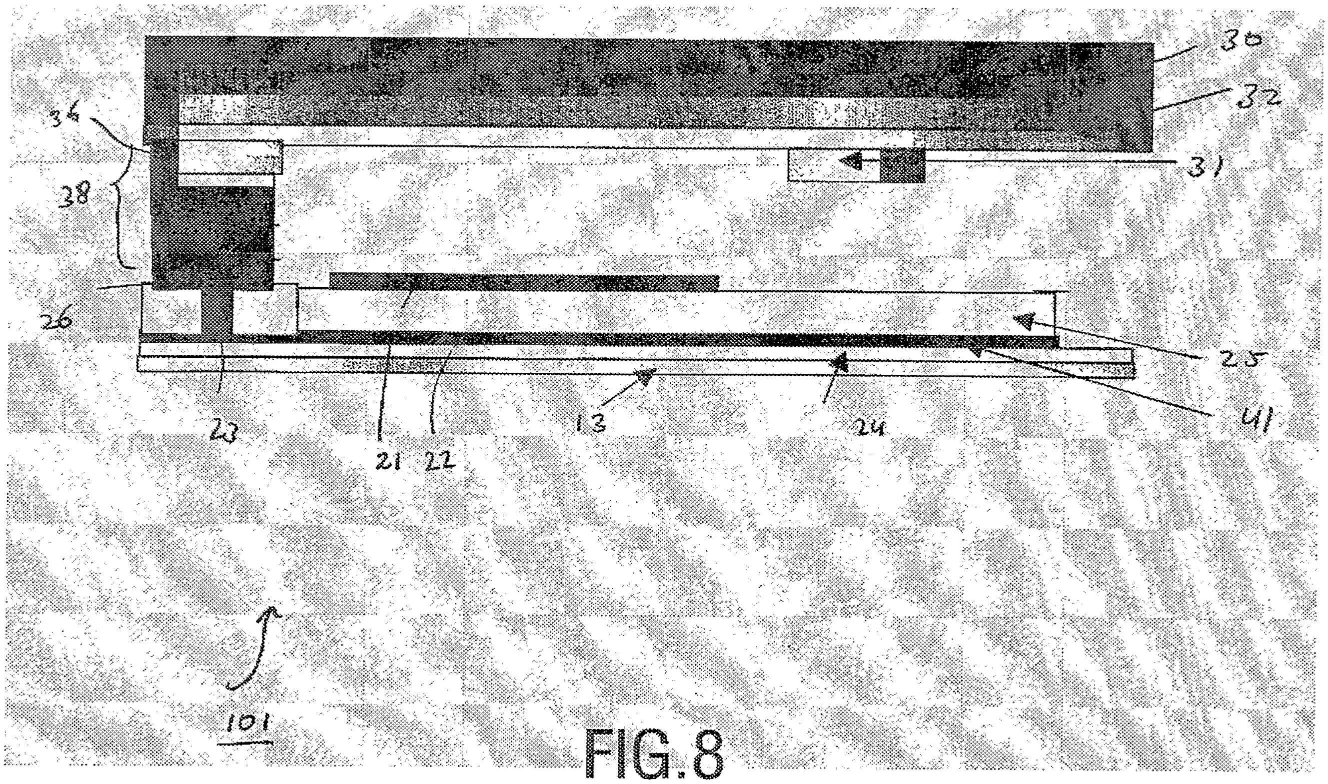


FIG.7


30
32
34
38
31
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41
23
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24
21
22
101

FIG.8

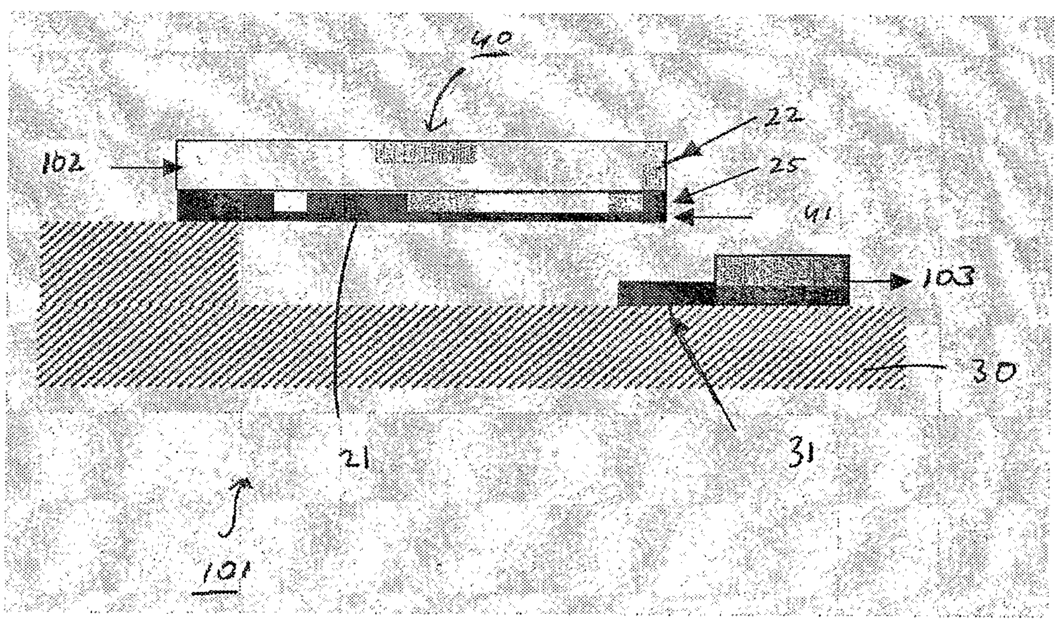
40
22
102
25
41
103
30
21
31
101

FIG.9

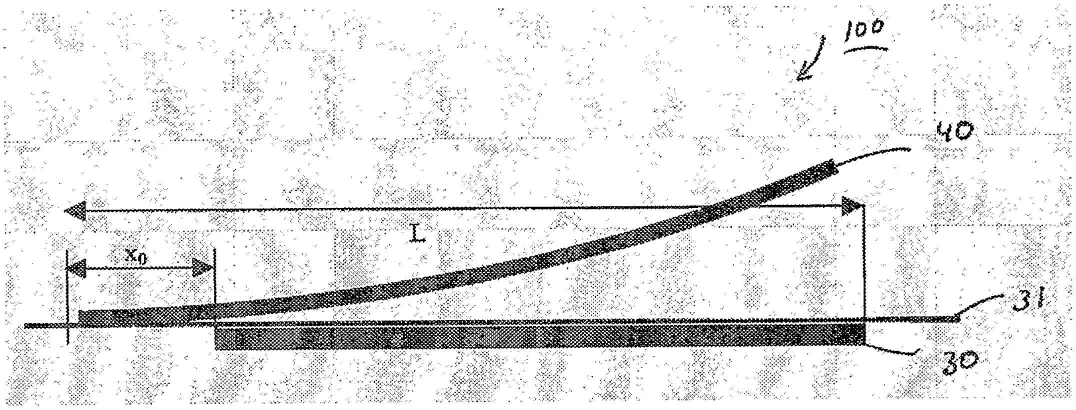
100
40
L
x_0
31
30

FIG.10

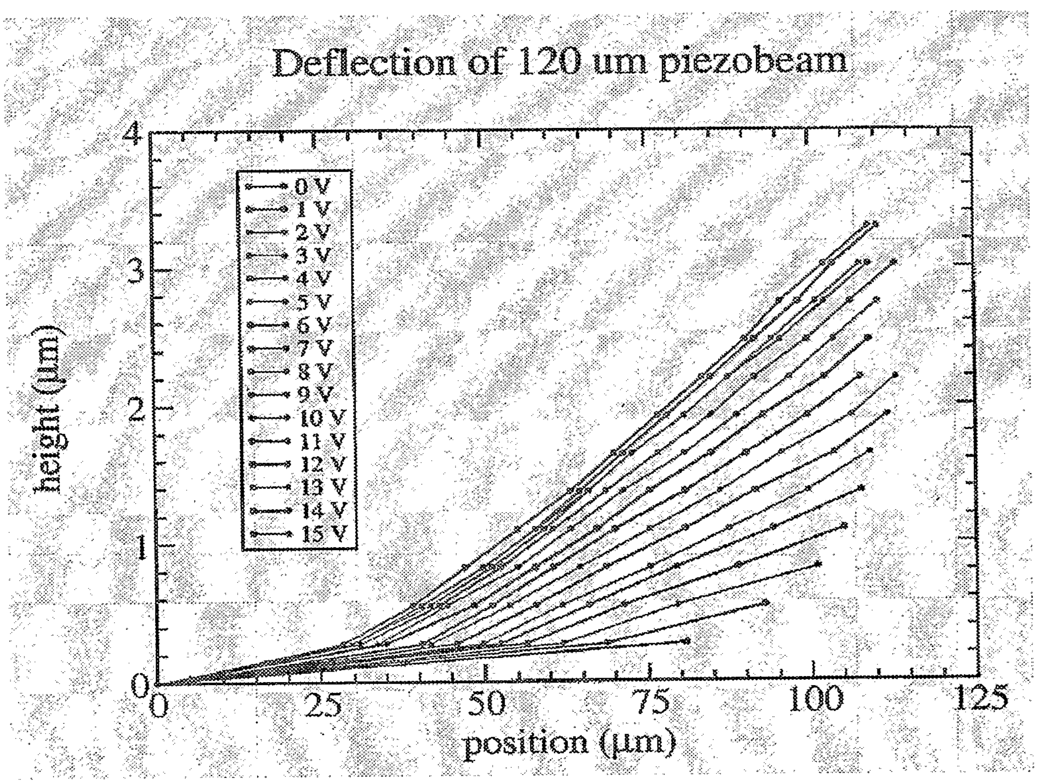
Deflection of 120 um piezobeam
height (µm)
position (µm)
0 V
1 V
2 V
3 V
4 V
5 V
6 V
7 V
8 V
9 V
10 V
11 V
12 V
13 V
14 V
15 V
0
1
2
3
4
0
25
50
75
100
125

FIG.11

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